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**SELF-TEACHING DIGITAL-COMPUTER
PROGRAM FOR FAIL-OPERATIONAL
CONTROL OF A TURBOJET ENGINE
IN A SEA-LEVEL TEST STAND**

by Robert E. Wallhagen and Dale J. Arpasi

Lewis Research Center

Cleveland, Ohio 44135



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SUMMARY

This report describes the design and evaluation of a digital turbojet engine control which is capable of sensing catastrophic failures in either the engine rotor speed or the compressor discharge static-pressure signal and is capable of switching control modes to maintain near normal operation. The control program was developed for and tested on a turbojet engine located in a sea-level test stand. The control program is also capable of acquiring all the data that are necessary for the fail-operational control to function.

Experimental results are presented to show that the fail-operational control for engine rotor speed or for compressor-discharge static pressure matches very closely the normal engine response. Results also show that a fail-operational control for a combined failure of engine rotor speed and compressor-discharge static pressure operates in a reasonable fashion, even though it is an open-loop control. Failure detection for catastrophic failures is demonstrated, and control mode switching from normal to fail-operational control is demonstrated during transient operation.

INTRODUCTION

In recent years the state of the art in flight-worthy digital computers has reached the point where digital computation is a serious choice for the control of all aircraft systems. These include the flight and navigation system, the engine propulsion control system, the inlet control system (where applicable), the cockpit and cabin environmental control system, and the weapons control system (military). A compelling reason for digital computation for all these aircraft systems is its ability to integrate all system requirements into an overall mission control system. Digital computation also offers in-

creased flexibility in being able to change control algorithms without hardware changes. Highly complex programs needed for optimal or self-optimizing control are more adequately handled digitally. Other interesting areas that can use digital computation to advantage include engine diagnostics, sensor failure detection, and fail-operational control.

The main purpose of the study covered in this report was to investigate the use of a digital computer for turbojet engine sensor failure detection and fail-operational engine control. In this report the term fail-operational control is used to mean a control that is able to encounter the failure of a sensed control variable and still be capable of normal or near normal operation. A fail-safe control, on the other hand, would set engine operating limits such that it is safe to run without the failed control variable, or in the case of a critical variable, would set one fixed operating point.

A secondary purpose of the study evolved part way through the program. Once the fail-operational control system was developed, it was realized that the data taking needed for the fail-operational control scheme could be done by the computer. Thus, a second purpose of the study was to demonstrate that the digital computer could be programmed to learn the information needed for fail-operational control while operating in its normal control mode. This concept would make the control program applicable to all turbojet engines of the same configuration with the identical control programs.

The experimental study was conducted in a sea-level static engine cell. The test engine was a single-rotor afterburning turbojet, although the study did not cover afterburning operation. The control signals included in this study were engine rotor speed and compressor-discharge static pressure. The fail-operational control was evaluated by comparing transient step responses of engine rotor speed and engine gross thrust with corresponding responses under normal engine control.

Control variable failures were limited to the rotor speed signal and the compressor-discharge static-pressure signal. Detection was limited to catastrophic failures only. A catastrophic failure is one where the measured signal goes very rapidly to zero or an upper saturation limit.

A prior study done at Lewis and presented in reference 1 investigated digital control of a turbojet engine and the effect of digital-computer update interval on engine response. The same digital computer, control program, and test facility were used in this study.

This report describes the following: (1) the experimental test facility, (2) the philosophy behind the fail-operational control, (3) the procedure whereby the computer could self-teach the information necessary for fail-operational control, and (4) the test results under actual fail-operational control.

SYMBOLS

A_8	exhaust-nozzle area, cm^2
N	engine rotor speed, percent
P_2	compressor-inlet total pressure, N/cm^2
p_3	compressor-discharge static pressure, N/cm^2
T_2	compressor-inlet total temperature, K
T_5	turbine-discharge total temperature, K
W_f	fuel flow, kg/sec
X_{vg}	compressor variable geometry position
α	throttle position, deg

EXPERIMENTAL CONFIGURATION

Engine Description

The engine used in this experimental study is illustrated in figure 1. Inlet air passes through inlet guide vanes into an eight-stage compressor. Air bleed doors are located on the third, fourth, and fifth compressor stages and along with the inlet guide vanes are referred to as the compressor variable geometry. The inlet guide vanes are mechanically coupled to the bleed doors, and the entire compressor variable geometry is driven by mechanically coupled hydraulic actuators located on opposite sides of the engine. The compressor variable geometry servomechanism control loop is scheduled to optimize compressor performance over its complete range of operation.

A fuel control regulates the fuel flow into the burner. The fuel flow passes through a pressurizing and drain valve and an overspeed governor before it enters the burner spray bars. The fuel and compressor variable geometry controls are located together in one of two hydromechanical packages located beneath the engine.

Control of the variable exhaust-nozzle area is provided by the other hydromechanical package. The output of this control is a mechanical position used to command three linear translating mechanical actuators coupled to the exhaust-nozzle unison ring. Motion of the unison ring moves the nozzle leaves and thus varies nozzle throat area.

Modifications for Digital Control

The Standard hydromechanical engine control system was modified (1) to permit selective substitution of either digital control or standard hydromechanical control of compressor variable geometry, fuel, and variable nozzle area and (2) to permit easy switching between the two types of control (for safety reasons). Hydromechanical computation of each control schedule was maintained, except for the compressor variable geometry. The hydraulic output from the standard hydromechanical control normally used to drive the compressor variable geometry actuators was inactivated. The compressor variable geometry control schedule was implemented on a special purpose electronic analog computer.

The block diagram of the experimental configuration is shown in figure 2. A servoamplifier, of the type described in reference 2, was used to drive a servovalve to form the compressor variable geometry position loop. The servovalve powered the standard actuators; and their position, as measured by an engine-mounted linear potentiometer, was fed back to the servoamplifier to close the position loop. The command to the compressor variable geometry servoamplifier could be switched from either the analog computer schedule or the same schedule programmed on the digital computer.

The main fuel control was left intact, with the exception of a four-way switching valve which was inserted in the engine fuel supply line just ahead of the overspeed governor. This allowed manual switching of engine fuel flow between the hydromechanical control and the digital control. The digital command scheduled the output of a fast-response fuel metering device (ref. 3) whose output was sent to the four-way switching valve. The selected fuel was ported by the valve to the engine, while the unselected fuel was ported to drain through a dummy load.

The standard hydromechanical exhaust-nozzle control determines the position of a mechanical arm located on the exhaust-nozzle-control package. This arm is normally used to drive a power pack which in turn drives mechanical screwjack actuators attached to the nozzle leaves through a unison ring. This system was modified by replacing the mechanical screwjack actuators with hydraulic actuators and closing a servomechanism position control loop around them in the same way as described for the compressor variable geometry control. The power pack was removed, and a linear variable displacement transformer (LVDT) was installed to measure the position of the mechanical arm. The LVDT output was scaled and linearized by an analog function generator so that the proper unison ring position command was presented to the exhaust-nozzle servoamplifier. The command to the exhaust-nozzle servoamplifier could be switched from either the analog function generator or an equivalent digital schedule.

Signal conditioners were used to provide high-level signals (-10 to 10 V) from the transducer measurements. Throttle position α was measured by attaching a rotary

potentiometer to the shaft of the throttle input to the hydromechanical fuel control. A static-pressure tap, attached to a high-response gage transducer, was used to measure compressor-discharge static pressure p_3 . Engine rotor speed N was measured by attaching a special gear to the engine-power takeoff and counting gear teeth with a magnetic pickup. The resultant frequency was converted to a voltage proportional to rotor speed before being routed to the digital system. Thermocouples were used for measurement of both compressor-inlet temperature T_2 and turbine-exit temperature T_5 . An absolute pressure transducer was used to provide an ambient pressure P_0 measurement for use in correcting p_3 to absolute.

The digital system ground was isolated from the experiment through isolation amplifiers. This arrangement eliminated the possibility of ground loops and provided relatively noise-free measurements.

Digital Computer

The digital computer used in the study is a 16-bit machine with 16 384 words of magnetic core storage. It has a read-restore memory cycle time of 750 nanoseconds. An interface unit to the computer contains a high-level multiplexer, a single sample-and-hold amplifier, and a 13-bit digitizer to provide analog-to-digital conversion of the six measured signals. Digital-to-analog conversion of the computer commands is also accomplished in the interface through 13-bit digital-to-analog conversion units. The analog commands for compressor variable geometry X_{vg} , fuel flow W_f , and exhaust-nozzle area A_9 are obtained through separate digital-to-analog converters. Programming of the computer is done through a teletype and high-speed paper tape reader and punch. All control programming is done in assembly language to conserve core storage and execution time. A detailed description of the digital-computer system is presented in reference 4.

Test Facility

The turbojet engine was located in a sea-level static test stand. Outside air entered the cell through large louvers in the roof. No provisions were available to control or alter the inlet air temperature. Temperature and pressure varied a small amount from day to day, and temperature varied considerably with seasons. However, for a given test of a few hours, both were essentially constant.

PROCEDURE

Design Philosophy

There is a very straightforward idea behind the development of this fail-operational control. The central idea is to synthesize each control variable of interest from the remaining sensed control variables. Then if a failure of a signal is detected, the controller simply switches modes of operation and uses the synthesized control variable in place of the failed sensed control variable.

In this study, the method used to synthesize a failed variable is to tabulate values of the particular variable in terms of the other sensed variables. This involves tabulating one sensed variable against a second for given values of the rest of the variables. Interpolation is used to find information between the fixed values in the tables. To cover a full operating range for all variables requires many tables. Empirical equations could have been derived from tabulated data; however, they are generally difficult to obtain and are less accurate over the whole operating range because of the essentially nonlinear engine relations.

Description of Normal Engine Control

For the purpose of this study, the normal engine control is the digital-computer control programmed with the standard hydromechanical engine control laws.

Before the fail-operational engine control is described and the tables that are needed are explained, a basic description of the normal or standard fuel control laws is necessary. The normal control operates by scheduling the ratio of engine fuel flow to compressor-discharge static pressure W_f/p_3 as a function of engine rotor speed N and the input command throttle angle α . The ratio W_f/p_3 is multiplied in the control by p_3 to yield the fuel flow command to the engine fuel valve. The schedules shift with varying compressor-inlet temperature T_2 . For a fixed T_2 , a sketch of a map of W_f/p_3 as a function of engine speed is presented in figure 3. The throttle angle α commands W_f/p_3 units inversely with engine speed and yields what is referred to as droop line speed governing. Steady-state operating conditions for the engine are indicated by the long-dash line. Thus, for a fixed throttle input α , the engine will be operating at a point a in figure 3. If the command input is changed to α_2 , the droop governing control will try to schedule W_f/p_3 units defined by the intersection of the α_2 droop line and a constant-speed line passing through point a . This value of fuel flow would surge or stall the compressor or overheat the turbine. Therefore, an acceleration limit is incorporated in the engine control which limits W_f/p_3 units to the inter-

section of the constant-speed line and the acceleration limit line. The increased fuel flow will accelerate the engine along the short-dash line to operating point b. A deceleration limit is also shown in figure 3. This limit is active during decreases in throttle angle to maintain sufficient fuel flow to prevent combustor blowout.

Design for Sea-Level Static Test

The sensed variables for the turbojet engine control include engine rotor speed N , compressor-discharge static pressure p_3 , compressor-inlet temperature T_2 , turbine-discharge temperature T_5 , and pilot command throttle angle α . The only sensed variables considered for fail-operation control development were N and p_3 . The problem of tabulating N or p_3 as functions of all the other variables is much simplified for the sea-level test, where T_2 and P_2 are essentially constant. It was determined empirically that engine speed can be synthesized solely as a function of compressor-discharge static pressure, and vice versa. This was true during both steady-state and acceleration-deceleration limit operation of the engine and was, of course, due to the repeatability of the control. In addition, it was determined that each was a single-valued function of the other. An exception to this occurs during T_5 override, when the exhaust-nozzle area is varied from its normal schedule to limit T_5 to 980 K. A modification to the normal control schedules for fail-operational work which eliminates T_5 override operation is described in this section.

The normal turbojet engine operation can be broken down into three limiting cases. If the pilot α input is changed very slowly, the engine operates on its normal steady-state operating line. If the α input changes very rapidly, the engine control sets engine operation to an acceleration limit or a deceleration limit. For the purpose of tabulating data for the fail-operational controls, only these three limiting cases were considered. To simplify the fail-operational control further, separate data for the deceleration limit were not incorporated. This could be done because the deceleration limit is a constant W_f/p_3 value as a function of speed (see fig. 3). If the synthesized speed variable being used by the control during a speed signal failure is in slight error during a deceleration transient, it will not affect the value of W_f/p_3 given by the deceleration schedule.

A plot of compressor-discharge static pressure p_3 as a function of engine rotor speed N for normal digital control is presented in figure 4. It can be seen that a problem exists for tabulating values during acceleration, as the normal control exhibits a rotor speed overshoot and undershoot during step changes to 100 percent speed. Thus, for some speeds near 100 percent, p_3 is double or even triple valued. To avoid this problem, the normal droop line control laws had to be modified slightly for fail-operational operation. The largest modification to the control was to limit the throttle

command α during acceleration to a value which would yield 98 percent rotor speed. When the engine had accelerated to 98 percent speed, the control would allow the α command to increase at a fixed rate limit until it reached the pilot's commanded value or a preset maximum limit, whichever was less. The present maximum limit, which is less than the normal maximum throttle stop, was included to compensate for an exhaust-nozzle schedule modification which was made to avoid T_5 override operation. Under normal scheduled operation the exhaust nozzle would close to its minimum area at approximately 100 percent speed. This would cause T_5 to exceed the 980 K limit, and the T_5 override circuit would open and modulate the exhaust-nozzle area to maintain T_5 at 980 K. This modulation of the exhaust-nozzle area as a function of T_5 would affect the simplified p_3 against N relation near 100 percent speed and thereby make it impossible to synthesize accurately either N from p_3 or p_3 from N . Thus, the exhaust-nozzle schedule was modified for fail-operational control to include a minimum area limit that was larger than the normal minimum area. With this larger minimum area, T_5 override was avoided; however, the decreased nozzle resistance caused a 2- to 3-percent rotor overspeed at maximum α . Thus, the present maximum limit was included on the α command for fail-operational control. A final modification to the normal control for fail-operational operation was to change the droop line slopes above 85 percent rotor speed. The droop slopes were changed to three-quarters of their normal values.

A generalized block diagram of the fail-operational control is presented in figure 5. It shows how a failure detector on either N or p_3 will switch the control input from the real sensor signal to the synthesized signal. Either of the failure detectors will also switch the control outputs from their normal scheduled values to fail-operational outputs that include the control modifications to the α input, the exhaust-nozzle area limit, and the droop slope.

The actual tabulated data for the N and p_3 fail-operational controls are plotted in figure 6. In the computer program N is tabulated against p_3 for pressures from 13.8 to 69 newtons per square centimeter at increments of 1.38 newtons per square centimeter; p_3 is tabulated against N for percentages of maximum speed from 40 to 110 percent at increments of 2 percent speed. The data for p_3 against N and N against p_3 are essential redundant information and are stored separately in the computer for ease of access.

Both tables of data are plotted together in figure 6. Figure 6 presents data for both steady-state operation and operation during acceleration. The plot of acceleration data stops at 95 percent speed because the normal control comes off the acceleration limit at that speed. The data in figure 6 were learned by the self-teaching program which is described in the next section. Data are presented only from 53 to 99 percent because those were the limits of steady-state operation for the given test. The program fills in

the bottom and top of the tables with preselected values, so there is no danger of the fail-operational control reading a zero or blank table location.

A third mode of fail-operational control was developed for combined N and p_3 signal failures. This control was simply an open-loop schedule of steady-state engine fuel flow W_f as a function of α . The tabulated data for steady-state W_f as a function of α are presented in figure 7 (upper left plot). Although only one table of data was needed for W_f scheduling, two more tables were needed for complete operation. One of these tables, the upper right plot in figure 7, was steady-state engine rotor speed N as a function of α . This table is needed because the compressor variable geometry control is a schedule of commanded variable geometry position against engine corrected speed. These first two tables depend upon steady-state engine operation. To ensure operation close to steady-state, the combined N and p_3 fail-operational control mode was designed with a rate limit for increases in α . Thus, if the pilot commanded maximum α , the control would act as though the pilot was moving the throttle very slowly up to maximum. There was no limit for decreasing α , because all steady-state W_f commands are above the deceleration limit and close adherence to the variable geometry schedule is not critical during deceleration. To avoid deviations from steady-state operation that could occur if a combined N and p_3 failure occurred during a transient, a third table was needed. This table (lower plot in fig. 7) contained α as a function of steady-state engine speed. When a combined N and p_3 failure was detected, this third table was entered with the last value of engine rotor speed to determine the effective steady-state pilot throttle angle. This α command was then increased at the fixed rate limit until it matched the pilot's command.

Again it will be noted that there are redundant tabulated data in the digital-control program. There are separate tables for N against α and α against N as well as the previously mentioned N against p_3 and p_3 against N tables for both steady-state and acceleration operation. These were included because storage space was no problem and the available interpolation routine required abscissa data at even increments.

For the first try at using the fail-operational program, data were taken manually during normal operation to fill the required tables. This was done through a steady-state data acquisition system and by using x,y-plotters and strip recorders for the dynamic data. Then the data were scaled and manually programmed into the digital computer. At this point it became obvious that the computer could be programmed to do the data taking necessary to fill the tables. Such an addition to the computer fail-operational program could be called a self-teaching mode.

Description of Self-Teaching Program

There are two types of tables needed for the complete fail-operational control program. These are the steady-state data tables and the data tabulated during operation on the acceleration limit line.

During normal operation, under digital control the digital computer is sampling all control variables every 15 milliseconds or $66\frac{2}{3}$ times per second. To determine if the engine is operating at steady state, all variables are checked to see if they have changed more than 0.25 percent of their full-scale value during the last five sampling intervals. If none of the variables have changed more than the 0.25 percent, the control program assumes the engine is at steady state. All the variables of interest are then set aside for storage. The routines to do the actual storing are discussed in this section. As part of the normal control calculations, W_f/p_3 units are calculated by using both the droop line and the acceleration limit. A selector then chooses the lesser of the two W_f/p_3 values. If the lesser value is the acceleration limit value, indicating operation on the acceleration limit, an acceleration limit indicator latch is set. This latch is used in another portion of the normal control to set the exhaust nozzle to a fixed, substantially open area for quick acceleration. This latch is also used by the self-teaching program. Whenever the latch indicates operation on the acceleration limit, the control sets aside readings of all variables of interest for storage in the acceleration limit tables.

All of the tables are predefined in terms of the range and increment of the abscissa variable. For example, for the tables of N against p_3 , p_3 is the abscissa variable and the table is defined for a range of 13.8 to 69 newtons per square centimeter in increments of 1.38 newtons per square centimeter. The ranges of all tables and the increment sizes are listed in table I. The storage routine takes the data and determines if the abscissa variable matches a location in the table to within ± 20 percent of the table increment. If the abscissa variable meets this requirement, the ordinate variable is stored in the table. A counter is provided to count the number of times data are stored in each table slot. All new data are averaged with the previously stored data. A limit can be set such that after that number of data points are averaged, future data are ignored. If a sensed variable signal failure is sensed, the teaching routines are locked out to prevent the control from learning any additional data. To prevent the fail-operational control from using a table that is not completely filled, a check routine is used prior to switching to the fail-operational mode. This check routine generates data for any blank slots in the table by interpolation, using data above and below the blank slot. The routine was programmed to handle up to two blank slots in succession. The check routine also fills in the top and bottom lines of the table with predefined values. This feature is needed because during the learning process the engine may not be run to the extremes of its operating range, and the tables have to be defined to cover all possible extreme conditions.

Thus, portions of the tables at the low and high end remain blank during normal operation and learning.

An indicator routine was built into the fail-operational control to determine if the tables were filled. It checked the counter for each table location to determine if there were a given number of data points averaged for all locations. The indicator routine controlled a panel of display lights that could be used for a cockpit display. There were separate lights for each table to indicate if each table was considered learned. There was also a display light that was lit when the teaching program determined steady-state operation. Display lights were also provided to indicate which sensed variable failures had occurred and when the computed α command was being rate limited (because of failure of both p_3 and N).

The self-teaching program is capable of learning and filling a sufficient amount of all tables in less than 5 minutes of operation under normal control. All that is necessary is one slow ramp from idle to 100 percent speed to learn the steady-state tables and one or two full acceleration transients from idle to 100 percent speed to learn the acceleration limit tables.

Feilure Detection

As was stated in the INTRODUCTION, failure detection was limited to detecting catastrophic failure in the sensed signals for N and p_3 . Catastrophic failure was indicated when the rate of change of either variable exceeded a preset value. Because the control sampled all variables at a fixed frequency, the difference between two successive samples indicated rate of change. This difference between two successive samples was limited to 6.4 percent speed for N and 4.4 newtons per square centimeter for p_3 . Any change greater than those limits indicated a failure. The limits used were rather arbitrary, but they reliably indicated catastrophic failures. For a time between samples of 15 milliseconds used by the control, these absolute change limits translated to rates of 430 percent speed per second and 290 newtons per square centimeter per second. Both of these limits were far above anything that would occur during normal engine steady-state or transient operation. To avoid the possibility of sensing a false failure due to a large noise spike, the failure detection program waits for four successive samples to remain outside the absolute change limit.

The failure detection program is capable of switching back to normal control if a failed signal corrects itself. The program continues to monitor the failed signal and compares it to the synthesized value used for fail-operational control. If the sensed signal comes within fixed preset limits of the synthesized signal, it is assumed that the

failure no longer exists. The fixed limit to determine when a failure is corrected is equal to one-half of the limit that determines failure.

RESULTS

The fail-operational controls for both engine rotor speed and compressor-discharge static pressure were evaluated by comparing step responses of engine rotor speed and gross thrust with the same responses obtained under normal control. A plot of the step responses of engine rotor speed for the normal control, the N fail-operational control, and the p_3 fail-operational control is presented in figure 8. The step responses are from idle to the 100-percent speed setting. As shown in figure 8, the responses are essentially identical from idle to the 95-percent speed point. Above 95 percent speed the normal control exhibits a marked overshoot and undershoot of the 100-percent speed point. The two fail-operational controls exhibit a very slight peak prior to following the rate limited α to the maximum setting. The fail-operational controls do not quite reach the military setting because of slight discrepancies in their data tables. To avoid having these discrepancies cause an overspeed condition the preset maximum limit on the α command is set slightly lower than needed to compensate for the exhaust-nozzle area A_8 modification. The response did not start from 50 percent speed because the idle throttle angle setting did not yield 50 percent rotor speed for the particular inlet temperature for which the data were taken.

Figure 9 shows the step responses of engine gross thrust for the same controls and conditions as for figure 8. The responses are essentially identical for time up to 2.35 seconds, which corresponds to the 95-percent engine speed point. The final thrust values for the fail-operational controls are lower than those for the normal control because of the modified A_8 schedule. With the A_8 area held more open during fail-operational control to avoid surpassing the T_5 limit, maximum thrust can not be obtained. However, the fail-operational controls still obtain more than 92 percent of the normal thrust. The difference in final values between the N and p_3 fail-operational controls is due to the difference in their final speed settings (note fig. 8). For a short period, between approximately 2.35 and 2.75 seconds, the fail-operational controls exhibit more thrust than the normal control. This is due to the fact that the fail-operational controls come off the acceleration limit before the normal control. The exhaust-nozzle control commands a substantially more open acceleration area when the engine is operating on the acceleration limit. This acceleration area ensures fast acceleration, but it does not yield fast thrust response. When the exhaust-nozzle area closes from its acceleration area setting at high engine speeds, thrust increases rapidly. Thus, for a short duration of time the fail-operational controls command a more closed A_8 and hence more thrust.

The response of turbine-discharge temperature T_5 for the normal control and the N and p_3 fail-operational controls is presented in figure 10. It is presented to show that the simple limit on the A_8 schedule easily avoids T_5 temperature extremes. The normal control has a T_5 limit set at approximately 980 K. A T_5 control circuit overrides the normal A_8 schedule and modulates A_8 area to control T_5 to its maximum limit. The difference between the final T_5 values for the two fail-operational controls is again due to tabulation inaccuracies.

Figure 11 presents a plot of the digital-computer-generated W_f/p_3 command as a function of engine rotor speed for the transient responses of figures 8 to 10. This plot is presented to show how the fail-operational controls come off the acceleration limit at a lower α setting and how the droop slope is changed to three-quarters of the normal slope. The difference in the point where the N and p_3 fail-operational controls leave the acceleration limit line is due to the synthesized value for N in the N fail-operational control being slightly off. The p_3 fail-operational control knows the actual rotor speed, so its droop line is defined correctly.

The response of engine rotor speed for the combined N and p_3 fail-operational control is presented in figure 12. The response time is 30 seconds from idle to 99 percent speed. This control was programmed to show the capabilities of the digital control, and no effort was spent in trying to optimize it. The response of engine thrust for the combined N and p_3 fail-operational control is presented in figure 13. In comparing thrust output with figure 9, it is noted that the combined failure control has the least final thrust, approximately 87 percent of the normal control maximum thrust. This again is due to inaccuracies in the tabulation process. The table of W_f against α is especially susceptible to inaccuracies because the change in W_f per change in α increases rapidly at high α values. Because of these table inaccuracies, the maximum α limit had to be set lower than for the other fail-operational controls. Thus, although the rotor speed almost reached 99 percent, it was for a more open A_8 and hence a lower T_5 and lower gross thrust.

Figures 8 to 10 amply show how well the fail-operational controls perform during transient operation. The next real test was to demonstrate how the control performed when a failure occurred during an acceleration transient. To demonstrate this, the same 50- to 100-percent rotor speed step responses were used. The step was initiated with the engine at idle under normal digital control. As engine rotor speed passed between 60 and 70 percent, a failure of either the N or p_3 signal was generated. Figure 14 presents the complete step response for both cases. A comparison with figure 9 indicates that the responses are essentially identical. There is no noticeable diversion from the normal acceleration path when either failure occurs. Figure 15 presents the thrust responses for the same cases as shown in figure 14. Figure 16 presents a time history of the digital-control throttle angle command. Up until a failure is detected, the

control α command is equal to the pilot's α input. After a failure occurs, the control α command is reset to the 98-percent steady-state rotor speed throttle angle setting. This acceleration α limit lasts until the engine reaches the 98-percent speed condition. The rate limit moves the α command up to the maximum failed α limit.

Figure 17 presents the time response of an idle to 100-percent speed step, starting under normal control and subsequently suffering an N failure at approximately 60 percent speed and a p_3 failure at approximately 70 percent speed. The engine continues to accelerate normally after the N failure occurs, but has to revert to the open loop, rate limited, fuel flow schedule once p_3 fails. Figure 18 presents the time history of the digital-control-generated α command for the transient shown in figure 17. For the first 3/4 second the control α command follows the pilot's input. After the N failure occurs, the α command is reset to the fail-operational acceleration limit corresponding to 98 percent steady-state speed. After the p_3 failure occurs, the control uses the last speed value (synthesized under N fail-operational control) and resets the control α command to the value that corresponds to a steady-state speed equal to the last speed measured. From this second α command reset, the α increases at a fixed rate limit to its maximum limit.

To evaluate the fail-operational controls for transients other than full idle to 100-percent speed steps, small steps in command α were used that moved engine speed through 5- and 10-percent speed changes. These small steps were set up for the following speed ranges (in percent): 50 to 60, 60 to 70, 70 to 80, 80 to 90, 90 to 95, and 95 to 100. The transient responses of engine rotor speed to these small throttle angle steps are presented in figure 19. The 10-percent steps are presented in figure 19(a) and the 5-percent steps in figure 19(b). The response of the fail-operational control is seen to be very close to that of the normal control except in two respects. The change in the 95- to 100-percent speed step is caused by the modification to the α command and exhaust-nozzle area. It is interesting, however, to note how similar the 90- to 95-percent responses are. For the 90- to 95-percent step the fail-operational controls are working with 3/4 slope droop lines and with the steady-state data tables, as the control does not reach the acceleration limit for that case. The other noticeable difference between responses occurs in the final values that were reached. This is especially evident for the N fail-operational control under the 60- to 70-percent step. It overshoots by 4 percent speed. This large discrepancy was caused by an error in the control program that was not discovered until all the data were taken. The error was in the portion of the program which determines whether to use the steady-state or acceleration limit data tables. The program uses the acceleration limit data table when the acceleration limit latch is set. The error was that, once the program started using the acceleration data table, it did not switch back to the steady-state tables until speed reached the 98-percent level. This error affected all the steps below 90 percent. The fact that the

speed response was low on the 80- to 90-percent step is due to the way the steady-state and acceleration curves cross each other (note fig. 4).

The final evaluation of the fail-operational controls for N and p_3 was based on frequency responses of speed to α at the 70-percent speed point and the 90-percent speed point. These frequency responses are presented in figures 20 and 21, respectively. Both figures show that, although the magnitude responses of the fail-operational controls drop off at slightly lower frequency than those for the normal control, they are very similar. The responses show that the transfer function from the throttle angle command α to engine rotor speed N is a simple lag with a break frequency that is a function of rotor speed. The break frequency varies from approximately 0.5 hertz at 70 percent rotor speed to approximately 1.5 hertz at 90 percent rotor speed.

SUMMARY OF RESULTS

A digital, self-teaching, fail-operational control for a single rotor turbojet engine was designed and evaluated. The control synthesized values for failed sensed variables from tabulated data taken during normal operation. These tables of data could be learned by the digital computer in less than 5 minutes of running time under normal control.

The fail-operational control, under a rotor speed N or a compressor-discharge static-pressure p_3 signal failure duplicated the normal control speed response at speeds below 98 percent. Above 98 percent speed, the fail-operational controls for N and p_3 operated with a rate limit on the input command. This yielded no overshoot on acceleration transients to 100 percent rotor speed, whereas the normal control exhibits a sizable overshoot followed by a similar undershoot before settling to 100 percent speed. The fail-operational controls set maximum speed to within 1 percent of the maximum speed of the normal control and produced a maximum thrust output of more than 92 percent of the normal maximum thrust.

A fail-operational control for combined N and p_3 failures was demonstrated. It ran the engine on an open-loop schedule of fuel flow to command input. Although the combined N and p_3 fail-operational control was not optimized, it accelerated the engine from idle to 100 percent speed in 30 seconds and reached almost 99 percent speed and better than 87 percent of maximum thrust.

A failure detection scheme was demonstrated that adequately detected catastrophic failures. The program was capable of returning to normal control from the fail-operational mode, if a bad signal corrected itself. The control could sense failures and

switch modes of control with barely noticeable effects, even during acceleration transients.

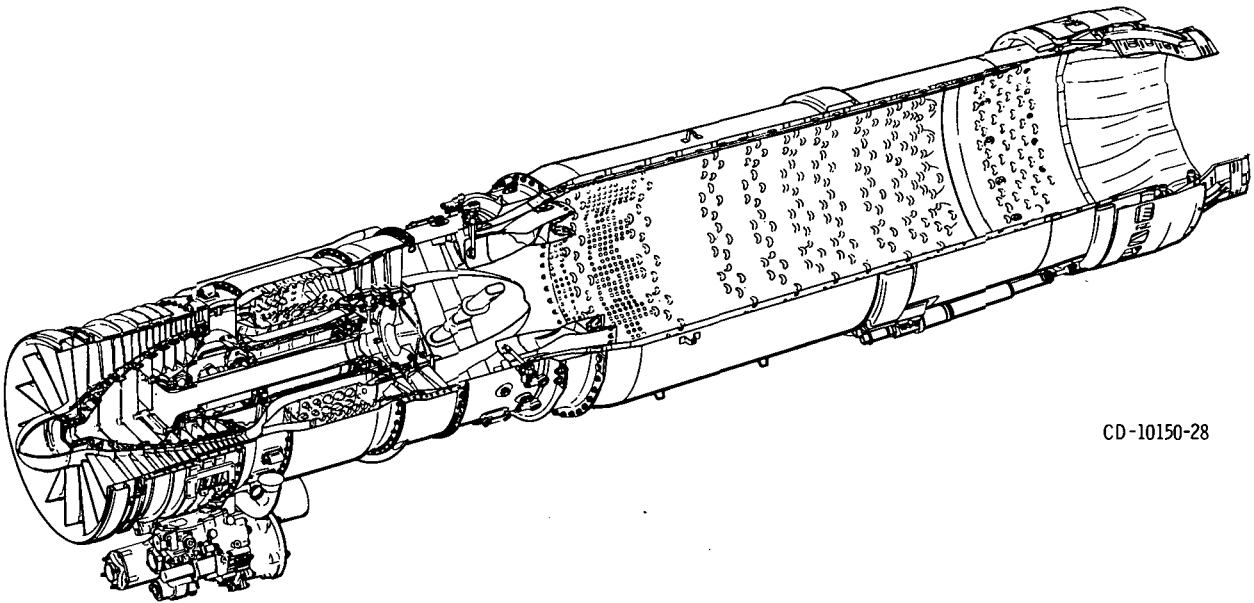
Lewis Research Center,
National Aeronautics and Space Administration,
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3. Batterton, Peter G.; and Zeller, John R.: Dynamic Performance Analysis of a Fuel-Control Valve for Use in Airbreathing Engine Research. NASA TN D-5331, 1969.
4. Arpasi, Dale J.; Zeller, John R.; and Batterton, Peter G.: A General Purpose Digital System for On-Line Control of Airbreathing Propulsion Systems. NASA TM X-2168, 1971.

TABLE I. - SELF-TAUGHT RELATIONS TABULATED BY COMPUTER PROGRAM

Variables tabulated	Type of table	Units	Independent variable	
			Range	Increment
N as function of p_3	Steady state	percent/(N/cm ²)	13.8 to 69	1.38
N as function of p_3	Acceleration limit	percent/(N/cm ²)	13.8 to 69	1.38
p_3 as function of N	Steady state	(N/cm ²)/percent	40 to 110	2
p_3 as function of N	Acceleration limit	(N/cm ²)/percent	40 to 110	2
W_f as function of α	Steady state	(kg/sec)/deg	12 to 78	2
N as function of α	Steady state	percent/deg	12 to 78	2
α as function of N	Steady state	deg/percent	40 to 110	2



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Figure 1. - Cutaway view of engine.

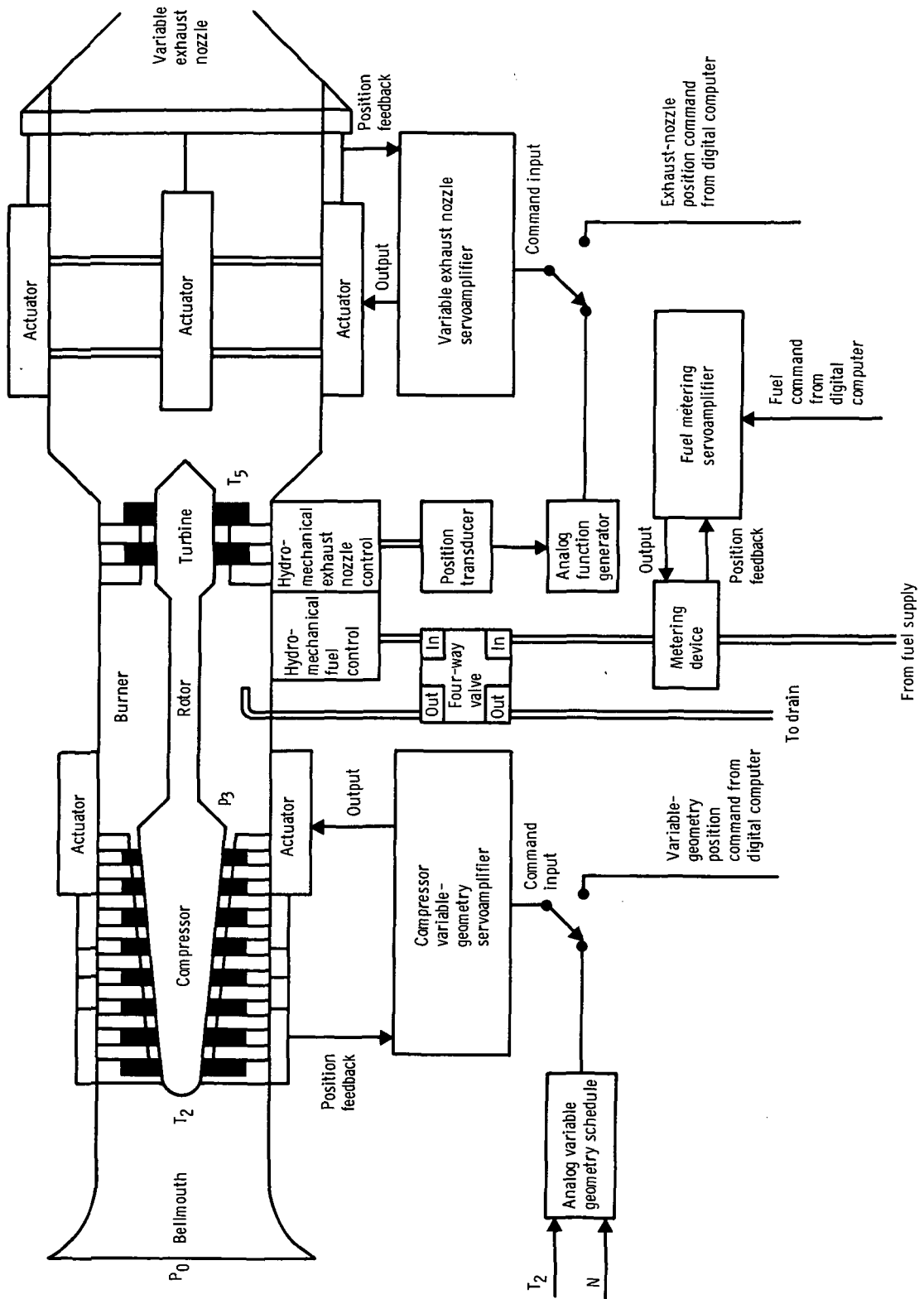


Figure 2. - Modifications to standard hydromechanical control system to permit switching to digital control system.

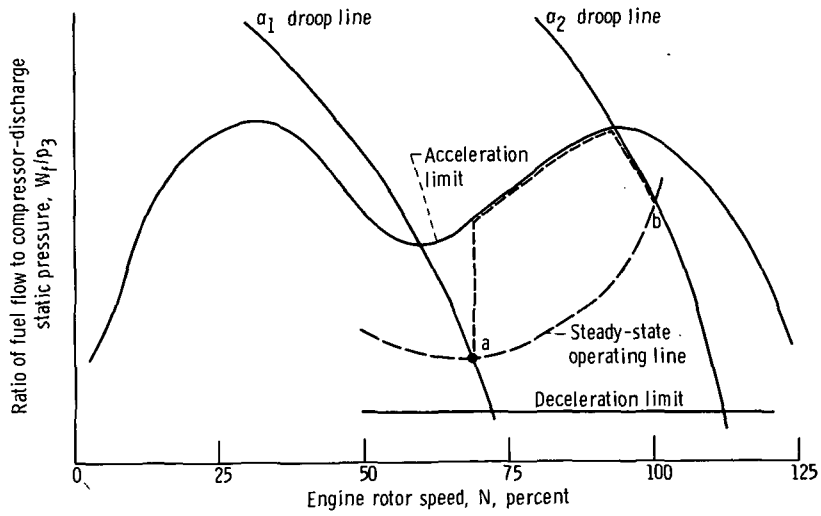


Figure 3. - Sketch of W_f/p_3 map used for normal engine control.

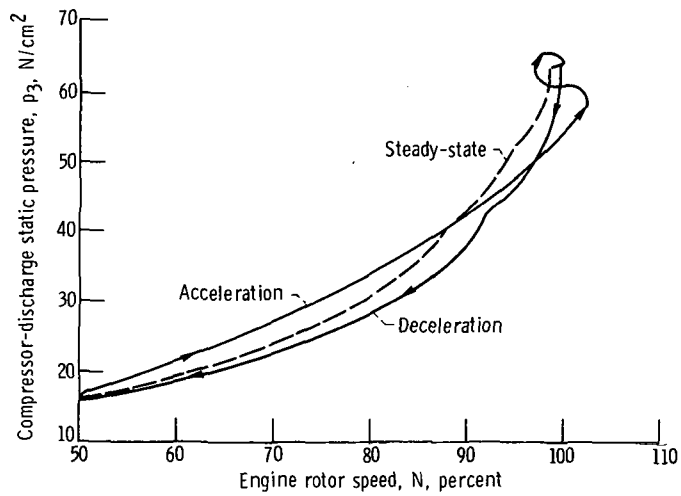


Figure 4. - Compressor-discharge static pressure as function of engine rotor speed for normal digital control.

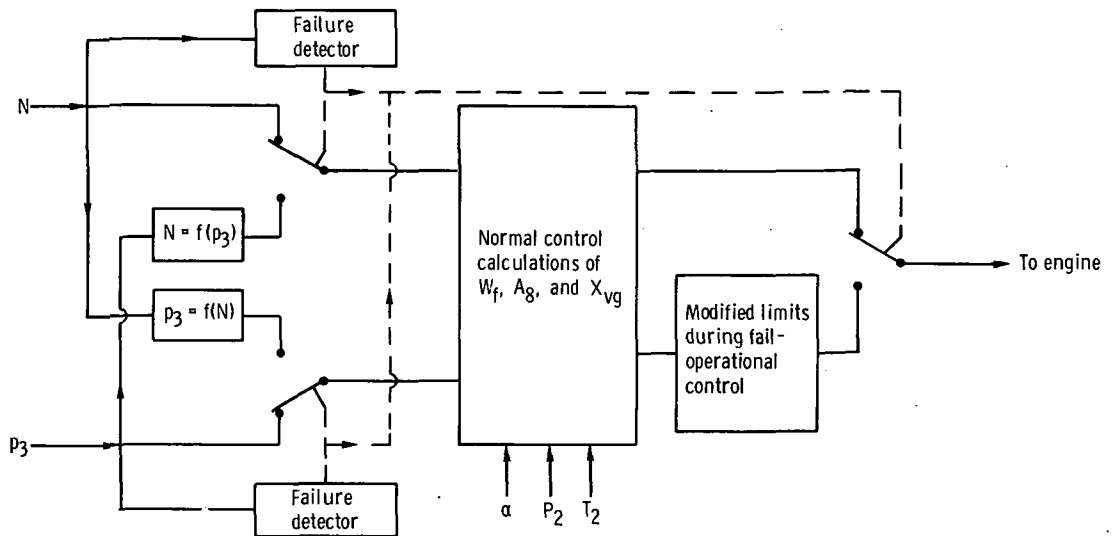


Figure 5. - Block diagram of fail-operational control.

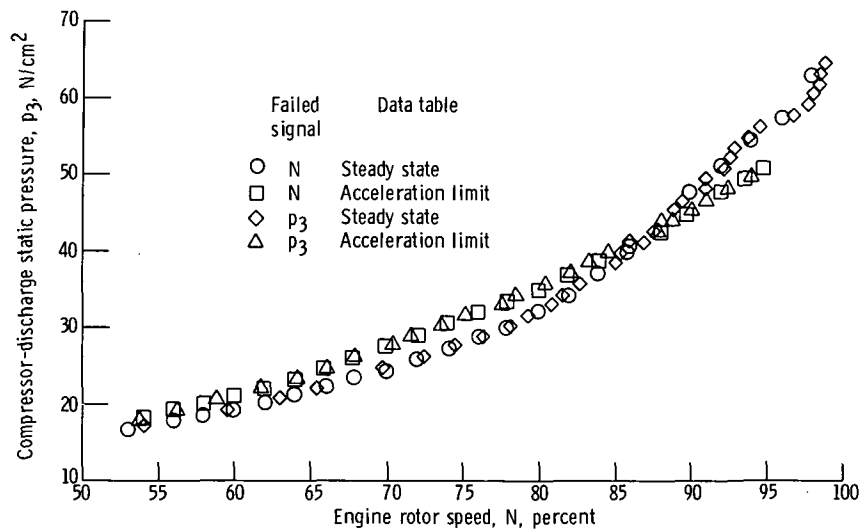


Figure 6. - Plot of tabulated values of compressor-discharge static pressure p_3 and engine rotor speed N as functions of each other for fail-operational control programs.

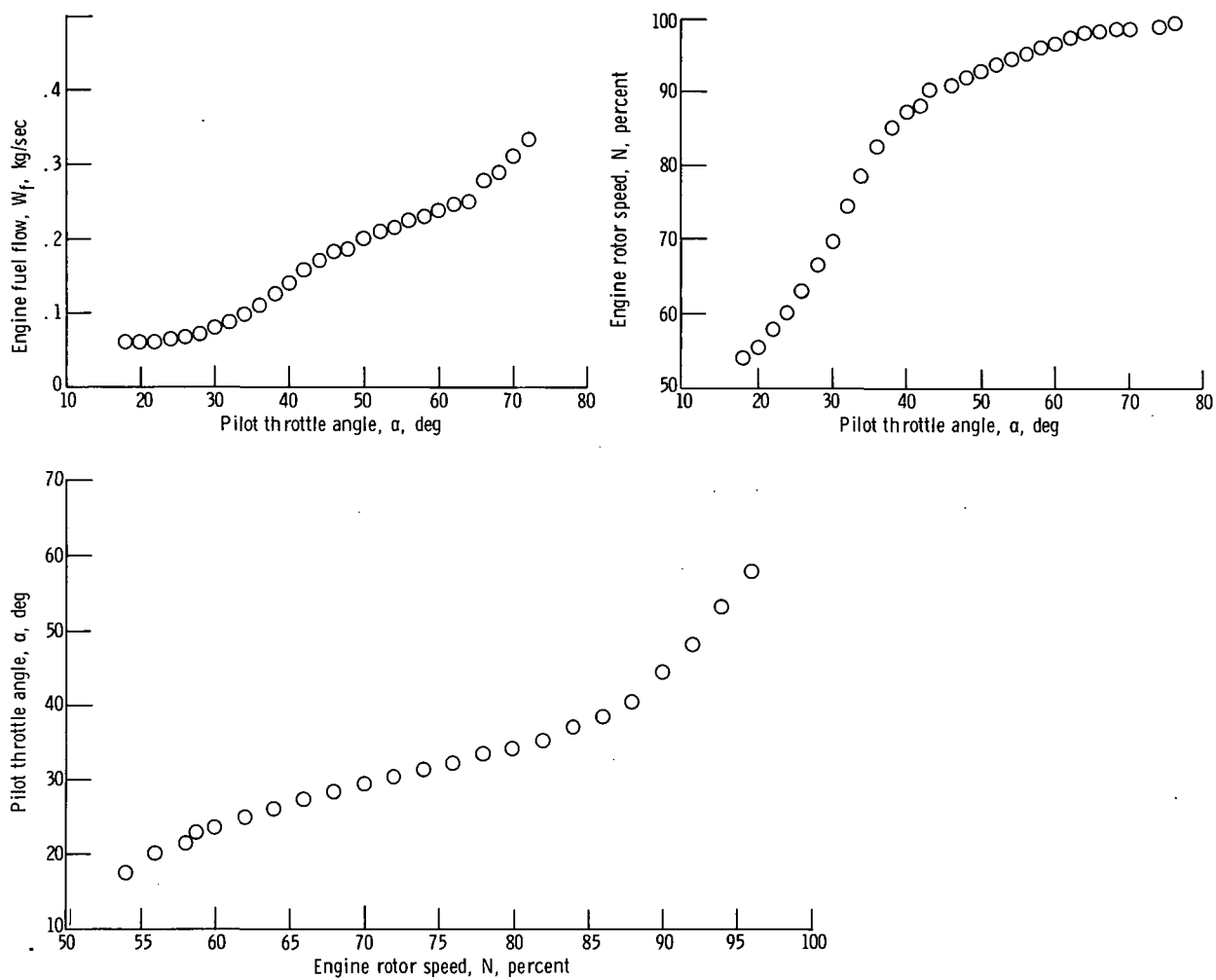


Figure 7. - Plots of tabulated data for combined compressor-discharge static-pressure and engine-rotor-speed fail-operational control.

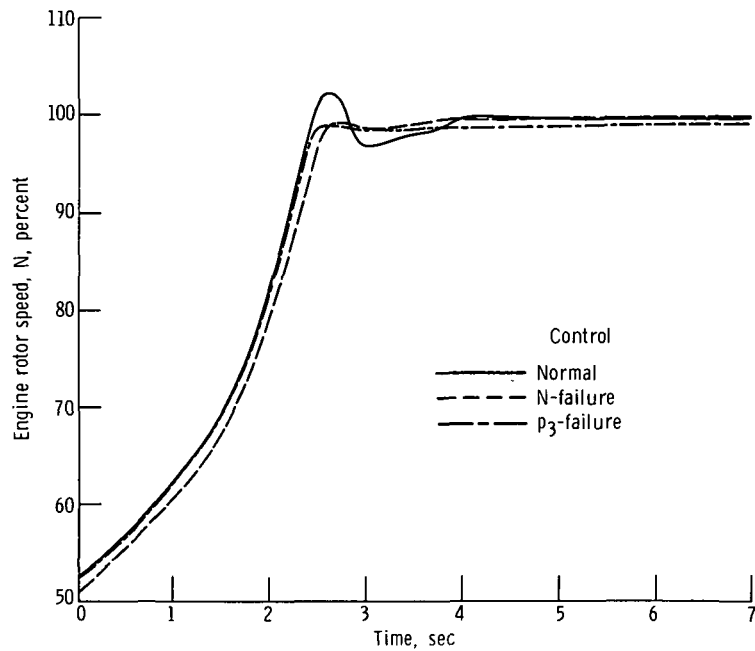


Figure 8. - Step responses of engine rotor speed from idle to 100 percent rotor speed for normal digital control and engine-rotor-speed N and compressor-discharge total-pressure p_3 fail-operational controls.

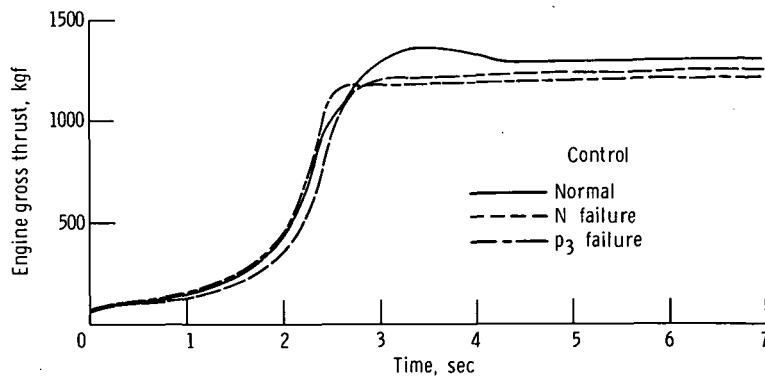


Figure 9. - Step responses of engine gross thrust from idle to 100 percent rotor speed for normal digital control and engine-rotor-speed N and compressor-discharge static-pressure p_3 fail-operation controls.

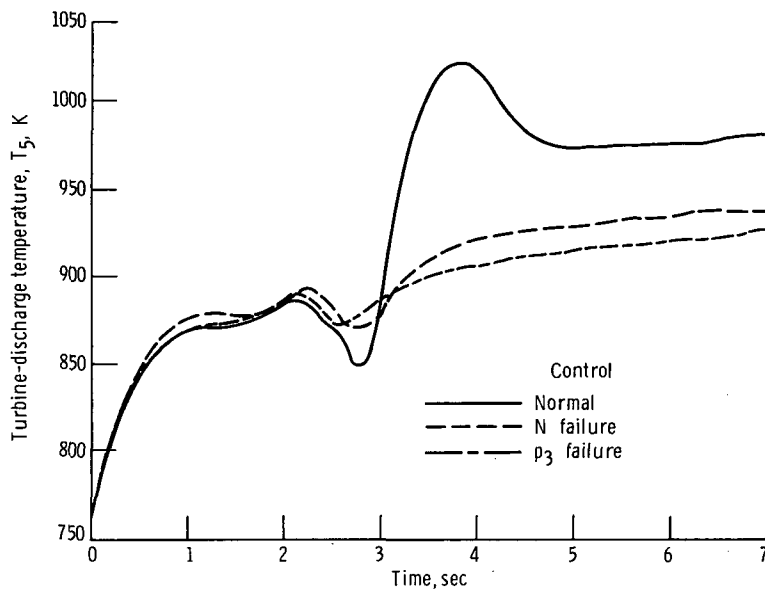


Figure 10. - Step responses of engine turbine discharge temperature from idle to 100 percent rotor speed for normal digital control and engine-rotor-speed N and compressor-discharge static-pressure p_3 fail-operational controls.

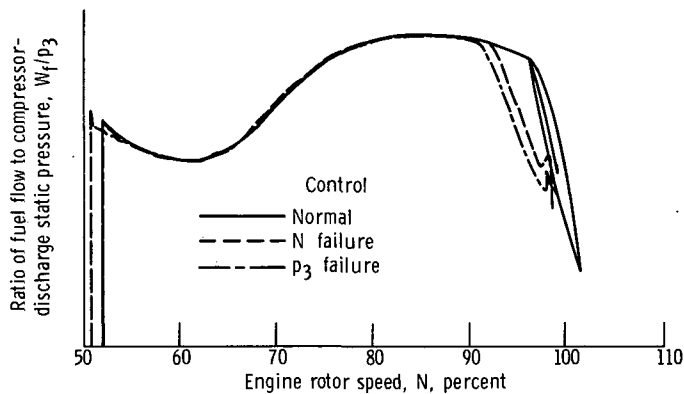


Figure 11. - Digital-computer-generated W_f/p_3 as function of engine rotor speed for normal control and for engine-rotor-speed N and compressor-discharge static-pressure p_3 fail-operational control.

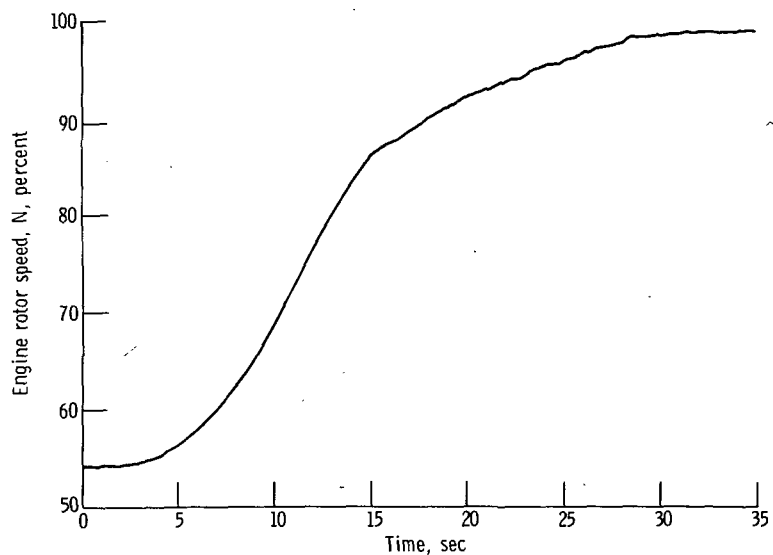


Figure 12. - Step response of engine rotor speed from idle to 100 percent rotor speed for combined engine-rotor-speed N and compressor-discharge static-pressure p_3 fail-operational control.

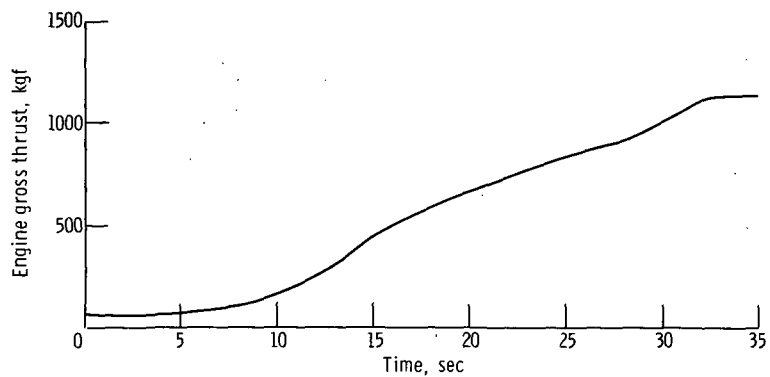


Figure 13. - Step response of engine gross thrust from idle to 100 percent rotor speed for combined engine-rotor-speed N and compressor-discharge static-pressure p_3 fail-operational control.

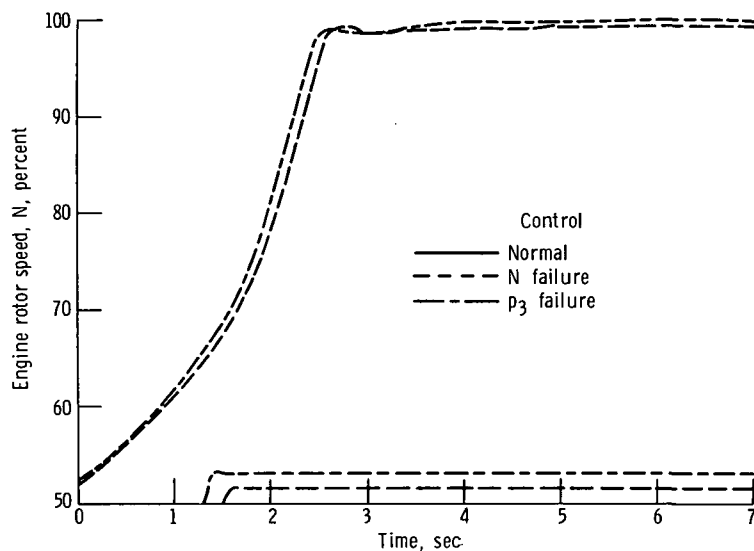


Figure 14. - Step responses of engine rotor speed from idle to 100 percent rotor speed with either engine-rotor-speed N or compressor-discharge static-pressure p_3 failure occurring during acceleration.

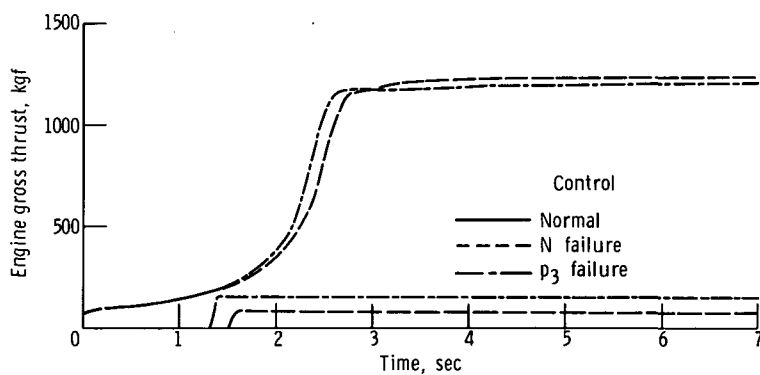


Figure 15. - Step responses of engine gross thrust from idle to 100 percent rotor speed with either engine-rotor-speed N or compressor-discharge static-pressure p_3 failure occurring during acceleration.

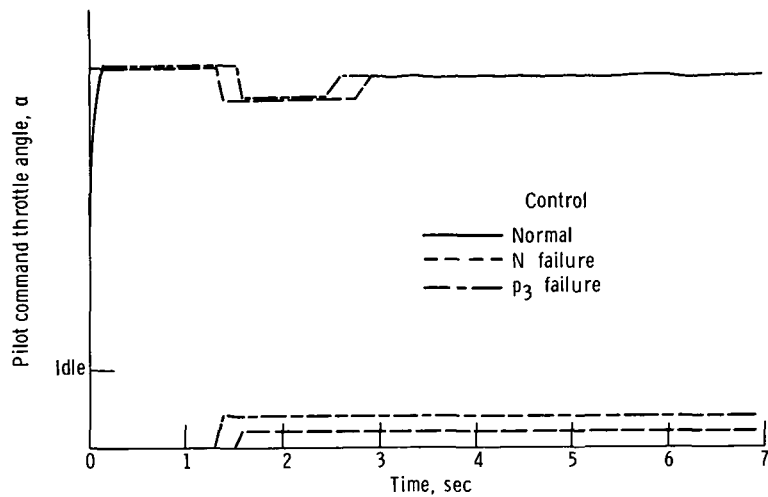


Figure 16. - Digital-computer-generated command throttle angle as function of time for test with either engine-rotor-speed N or compressor-discharge static-pressure p_3 failure during normal acceleration transient.

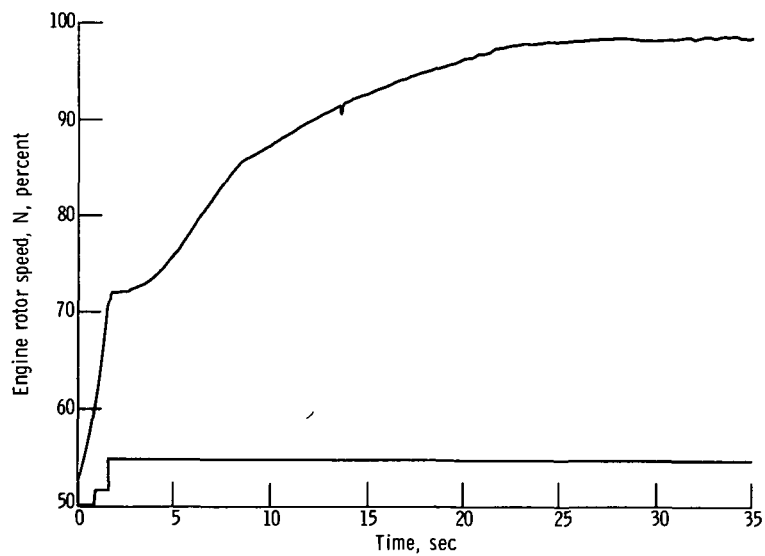


Figure 17. - Step response of engine rotor speed from idle to 100 percent rotor speed with both engine-rotor-speed N and compressor-discharge static-pressure p_3 failure occurring during acceleration.

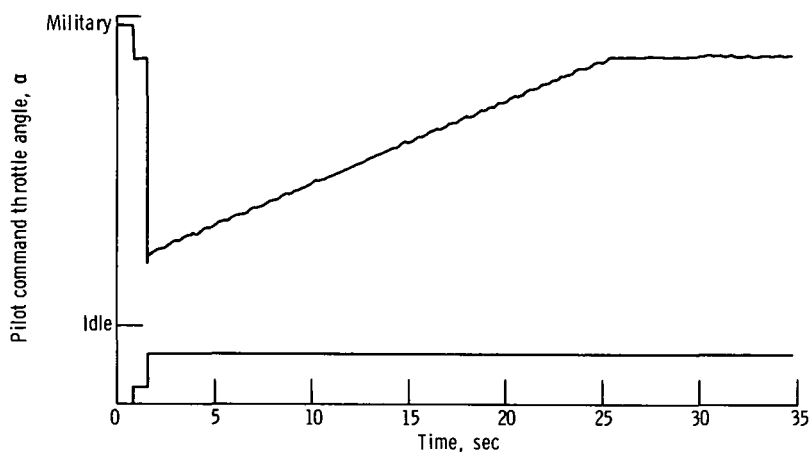


Figure 18. - Digital-computer-generated throttle angle as function of time for test with both engine-rotor-speed N and compressor-discharge static-pressure p_3 failure during normal acceleration transient.

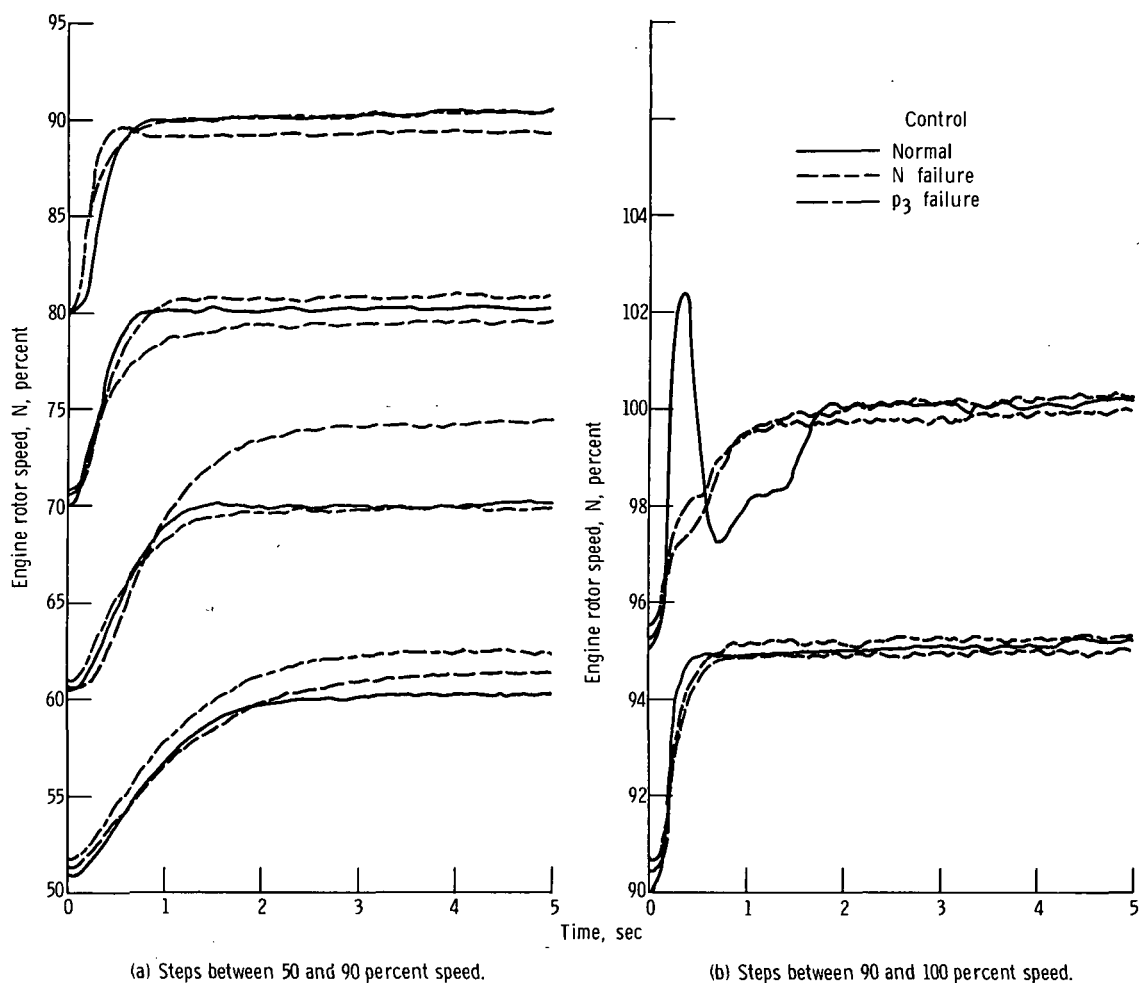


Figure 19. - Step responses of engine rotor speed for normal digital control and engine-rotor-speed N and compressor-discharge static-pressure p_3 fail-operational controls subjected to throttle-position steps equivalent to 10-percent changes in engine rotor speed.

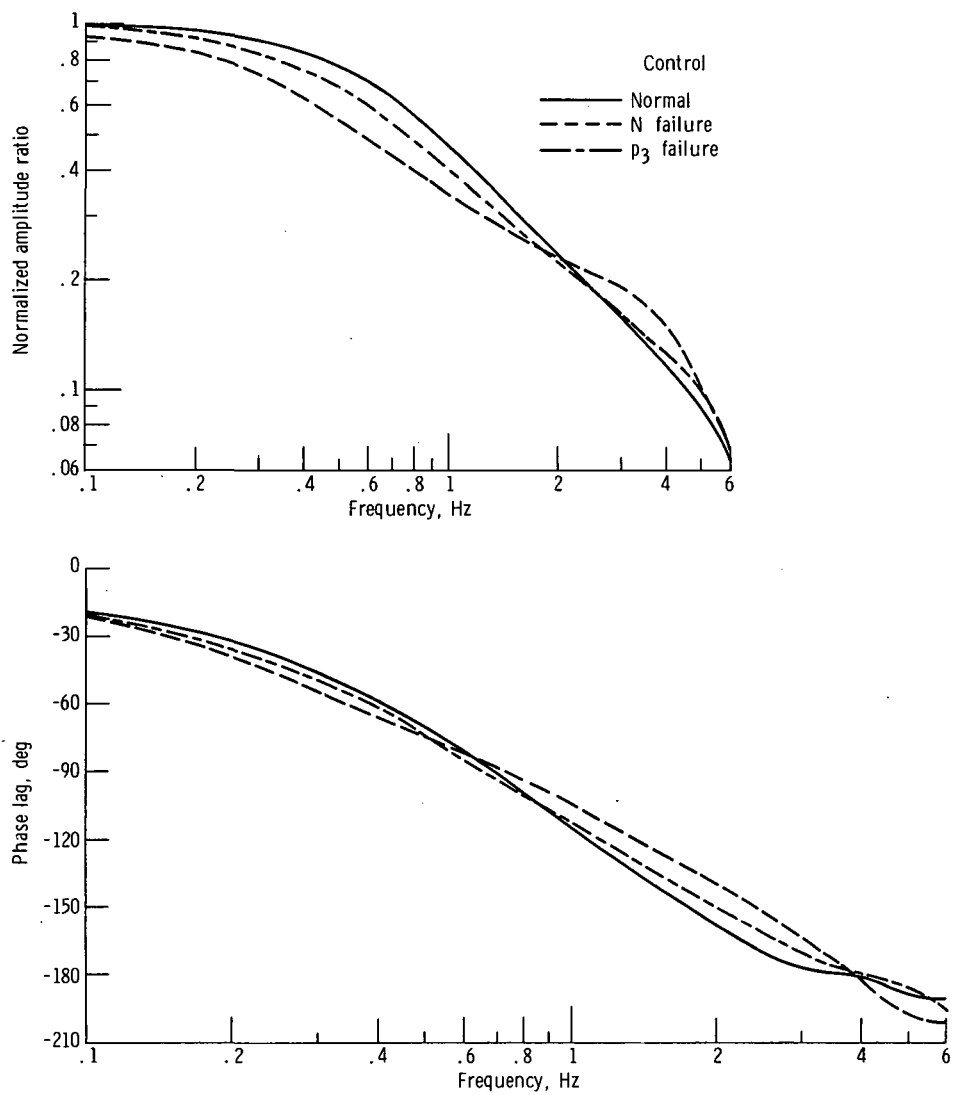


Figure 20. - Frequency response of engine rotor speed to command throttle angle. Engine operating at 70 percent speed.

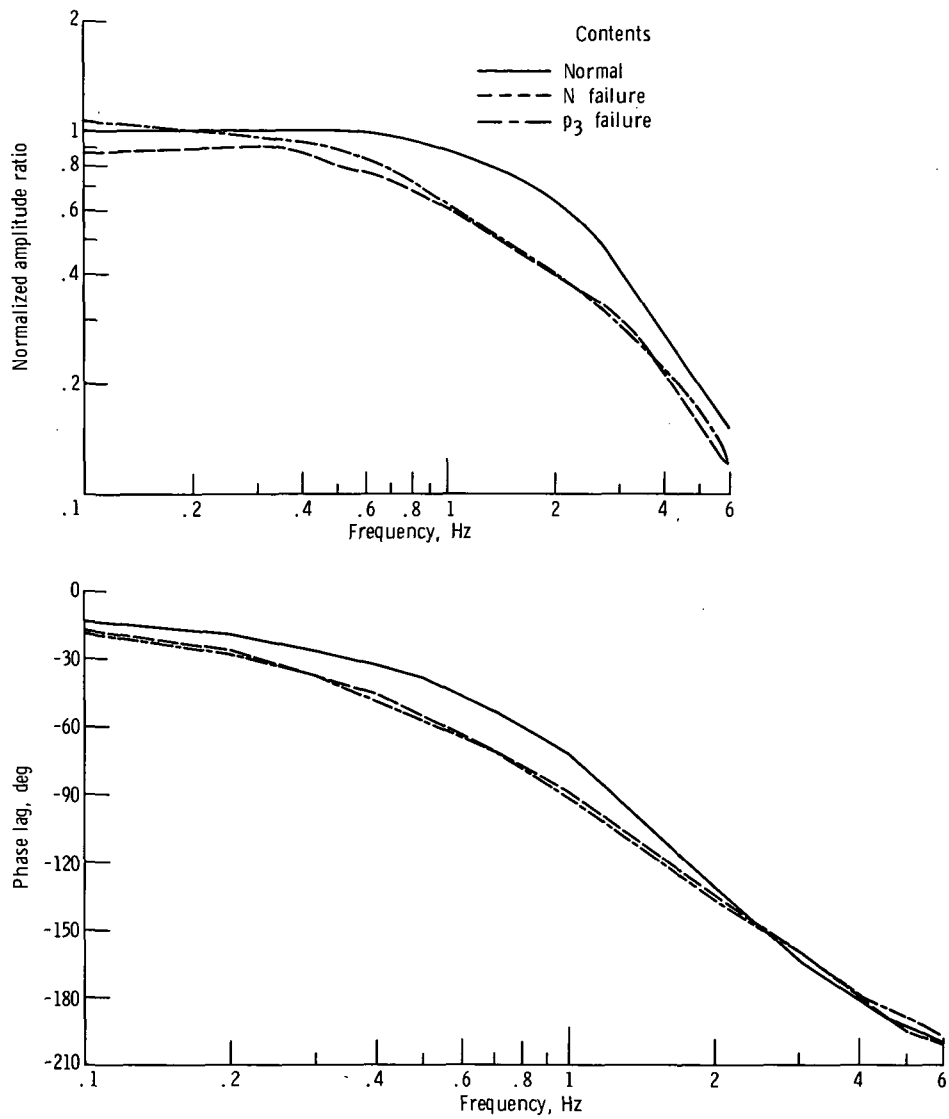


Figure 21. - Frequency response of engine rotor speed to command throttle angle. Engine operating at 90 percent speed.



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